FOAM EMISSIVITY MODELLING WITH FOAM PROPERTIES TUNED BY FREQUENCY AND POLARIZATION

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ABSTRACT

We model the sea foam emissivity as a part of the work done by an international science team on developing a radiative transfer model of reference quality for the ocean surface emissivity from L band to infrared frequencies. The focus here is on the foam emissivity at frequencies from 1 to 89 GHz. Sensitivity study for different foam properties (foam layer thickness and upper limit of the foam void fraction) guided the effort to tune the model by frequency and polarization. The results show that the differences between simulated and observed brightness temperatures decrease when using tuned foam model.

Index Terms— Ocean surface emissivity, sea foam emissivity, microwave radiometer, passive remote sensing.

1. INTRODUCTION

The skills of numerical weather prediction models improve with the assimilation of well-calibrated satellite observations [1]. Solid basis for any data assimilation system is a radiative transfer model (RTM) that represents the ocean-atmosphere coupling well. Challenges for building reliable RTM arise from: (i) The use of different models for different frequency and wavelength regions of the electro-magnetic spectrum; (ii) Lack of sufficient knowledge to model the physical processes occurring in the atmosphere, ocean, and on land; and (iii) Absence of well quantified uncertainty for the various model components. The modeling of ocean surface emissivity and reflectivity across a broad spectral range—from microwave to infrared (IR)—exemplifies how such challenges limit the quality of the RTMs in use. An ocean-atmosphere RTM of a reference quality is necessary to address the current challenges and limitations.

The International Space Science Institute (ISSI) has funded a project to develop a reference RTM for the ocean surface emissivity e from L band to IR (1 GHz to 100 THz) [2]. To this end, an international team has been working on developing a Passive and Active Reference Microwave to Infrared Ocean (PARMIO) model and providing its software on GitHub [3] for use by the modeling and remote sensing communities.

Modeling the sea foam contribution to e is one of several elements in PARMIO model all related together as follows:

$$e = (1 - W)(e_0 + \Delta e_r) + W e_f \tag{1}$$

where e_0 is the specular emissivity of flat sea surface, Δe_r represents emissivity increase due to roughness of foam-free sea surface, e_f is the emissivity of foam-covered surface, and W is the whitecap fraction (the fraction of a unit surface covered by sea foam) which serves as a weighing factor for the contributions of the roughness and foam components as wind speed changes. The investigation described here focuses only on the foam emissivity component e_f in (1).

Building on the incoherent approach to RTM [4], Anguelova and Gaiser (2013) model the foam emissivity e_f at WindSat nominal frequencies of 6 to 37 GHz [5] with a focus on the vertical stratification of the foam properties in sea foam layers [6]. Yin et al. (2016) adjusted the e_f model of [5] for L band [7] and incorporated it in the full (ocean-atmosphere) RTM of Laboratoire d'Océanographie et du Climat called LOCEAN originally developed by [8]. An updated version of this full LOCEAN RTM is used today in the Soil Moisture and Ocean Salinity (SMOS) operational processing [9]. Hereafter, we refer to [5] and [7] e_f models as 'NRL e_f model' and 'LOCEAN e_f model,' respectively.

Simulated brightness temperature $T_{B\text{sim}}$ at the top of the atmosphere (TOA) from the full LOCEAN RTM—based on the ocean surface emissivity e in (1) together with its foam emissivity component e_f as in [7]—has been assessed by [10] against collocated observations $T_{B\text{obs}}$ from satellites, Soil Moisture Active Passive (SMAP) for L band and Advanced Microwave Scanning Radiometer-2 (AMSR2) for C to W bands. Simulations with the full LOCEAN RTM deviate from the SMAP T_B observations by $\Delta T_B = T_{B\text{obs}} - T_{B\text{sim}} < \pm 0.5$ K for wind speeds up to 20 m s^{-1}. These ΔT_B deviations are small because the parameters in the full LOCEAN RTM, including those of LOCEAN e_f model (as part of e), are well adjusted for L band. However, ΔT_B goes up to + 4 K for the AMSR2 frequencies (Fig. 7-11 in [10]). One possibility to improve e in the full LOCEAN RTM (and by extension any ocean

surface emissivity RTM) is to improve its foam emissivity e_f model.

The foam properties used to model e_f are foam layer thickness t and the vertical profile of the foam void fraction f_a in t with limits v_{af} and v_{fw} at the top (air-foam) and bottom (foam-water) boundaries of the foam layer, respectively. Previous analyses suggest that the e_f modeling improves (in comparison to available e_f observations) when t and the upper limit v_{af} are tuned for specific frequency and polarization [5]. The physical basis for this is that the skin depth of the foam changes when f_a (via v_{af}) varies so that the seawater content in the foam is re-distributed over different thicknesses t [6].

Published implementations of both NRL and LOCEAN e_f models have used so far constant values for t and f_a top and bottom limits. The NRL e_f model uses a log-normal distribution of thicknesses, which peaks at t = 3.54 cm and void fraction limits of v_{af} = 99% and v_{fw} = 1% [5]. The LOCEAN e_f model uses an effective foam layer thickness t = 2 cm and f_a limits of v_{af} = 95% and v_{fw} = 1% [7]. In this study, we investigate how much tuning e_f via foam properties affects the modeling of the ocean surface emissivity e in (1).

2. METHODS

The work involved three tasks: (i) Identifying and reconciling differences between implementations of the foam emissivity models; (ii) Tuning the e_f model variables representing the foam layer properties by frequency (L to W bands) and polarization (horizontal H and vertical V); and (iii) Assessing how the tuning of the e_f model affects e and thus the performance of a full RTM at TOA. Brief description of the methodology for each task follows.

2.1. Foam emissivity modeling

We compared the implementations of the NRL and LOCEAN e_f models, which are coded, respectively, in Interactive Data Language (IDL) and FORTRAN (F90). We reconciled the identified differences and quantified them in terms of percent difference (PD). The PD between two values x_1 and x_2 is defined as the ratio of their difference and their average: $\mathrm{PD} = |x_1 - x_2|/[(x_1 + x_2)/2] * 100$.

2.2. Tuning the foam emissivity models

We tuned the foam property variables t and v_{af} in two steps. First, we identified effective foam layer thickness for each frequency. We focused on the idea of effective thickness (as in LOCEAN e_f model) because of the continuing lack of well verified experimental data supporting one or another distribution of foam layer thicknesses (as exemplified in the NRL e_f model). To tune t, we started with a sensitivity study of the nominal thickness t_n of a foam layer, defined as the foam thickness over which the seawater skin depth for a given frequency is distributed for a given void fraction profile [6]. For each frequency from 1 to 89 GHz, we examined the variations of t_n when changing v_{af} from 75% to 99% (at fixed lower limit v_{fw} = 1%). We identified an effective thickness for each frequency from these results.

The positive deviations ΔT_B between simulated and observed T_Bs for frequencies above L band (Section 1) suggest that the full LOCEAN RTM consistently simulates lower $T_{B\mathrm{sim}}$ values. To decrease ΔT_B via foam modelling, the e_f values need to increase (with all other elements of e in the full RTM, such permittivity and roughness, the same). For a given effective thickness, e_f increases for higher upper limit of the void fraction. Because experimental values for e_f at C to W bands are still insufficient or missing, the only criterion for choosing specific v_{af} value was to produce smooth frequency dependence of e_f.

2.3. Assessing the effect of tuned foam emissivity

We assess the effect of tuned e_f values on e in a full RTM for 6 to 89 GHz by comparing simulated TOA T_B to AMSR2 T_B observations (as done in [10]). The AMSR2 dataset is the same one used in [10] (see Section 2.2 in [10]); it includes 987,235 data points of T_B values. AMSR2 data are collocated with surface and atmospheric parameters from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA)-Interim and from the Mercator Ocean reanalysis distributed by the Copernicus Marine Service.

We used an implementation of e with a full LOCEAN RTM from GitHub, which comprises modules for each component in (1), including a 2-scale model for roughness using Durden-Vesecky wave spectrum [7] and the LOCEAN e_f model. Wind speed at 10-m reference height U_{10}, sea surface temperature (SST), sea surface salinity (SSS), and air temperature at 2 m height (2AT) from the collocated ERA-Interim and Mercator data are inputs to those modules. The code offers a choice for the W parametrization in (1). We used the parametrization of [11], which obtains W with U_{10} and the atmospheric stability ΔT = 2AT − SST, i.e., $W(U_{10}, \Delta T)$.

We ran the full RTM from GitHub with no changes in the atmospheric and roughness modules at fixed incidence angle of 55° and at fixed environmental factors of SSS = 34 psu and SST = 20 °C. The only changes were for the foam parameters in 3 different cases. Case 1 (control) combines the LOCEAN foam property choices, namely fixed t = 2 cm and v_{af} = 95% for all frequencies and H and V polarizations [10] with $W(U_{10}, \Delta T = 0)$. Case 2 uses t and v_{af} specific for each frequency and polarization (tuned foam) with the same $W(U_{10}, \Delta T = 0)$. Case 3 is as Case 2 (tuned foam) but with a change to $W(U_{10}, \Delta T \neq 0)$. We considered the e_f tuning successful if the deviations ΔT_B obtained from e in the full RTM decreased compared to those in the control case.

3. RESULTS AND DISCUSSIONS

3.1. Reconciling foam emissivity implementations

The implementations of the NRL and LOCEAN e_f models differed in four ways. One was the use of different seawater

permittivity models: [12] in NRL and [13] in LOCEAN e_f models. Another was the inconsistent use of variables when obtaining the Fresnel reflectivity Γ_2 at the bottom of the foam layer. Also, different numerical integration approximations were used: the trapezoidal rule in the NRL e_f model and the Simpson rule in the LOCEAN e_f model.

Finally, and most importantly, the formulations of the incoherent approach for e_f differ. The NRL e_f model follows the most general formulation, as given in [5], with multiple numerical integrations for the upwelling and downwelling losses originating from different strata in the foam layer. The LOCEAN e_f model uses a semi-closed formulation, which combines the closed (analytical) form for emissivity of a non-stratified layer, as given in [4], with a total loss factor of a stratified foam layer obtained with only one numerical integration.

Figure 1 shows the frequency dependence of the foam emissivity $e_f(F)$ obtained with the original implementations of LOCEAN and NRL e_f models. With all differences in place, the discrepancy between the two implementations is less for V polarization than for H polarization. The PD is maximum of 0.15% for V pol at 1.4 GHz and much lower for all other frequencies, while it is maximum of 1.45% for H polarization at 36.5 GHz.

To reconcile these differences, we changed the seawater permittivity model to that of [14]; used consistent variables to obtain Γ_2; and used the Simpson integration rule in both implementations. The only difference left between the NRL and LOCEAN e_f models (besides the coding language) is the formulation of the emissivity incoherent approach, general versus semi-closed forms, respectively.

Figure 2 shows $e_f(F)$ when all differences are reconciled but the formulations of e_f. The PD for V polarization is below 0.04% with exception for 89 GHz (PD = 0.16%). The comparison of LOCEAN and NRL e_f models improves significantly for H polarization with PD changing from more than 1% (Fig. 1) to below 0.4% for all frequencies. The small discrepancies suggest that the semi-closed form of the incoherent approach used in LOCEAN e_f model—as compared to the generalized formulation in the NRL e_f model—is a good approximation for modeling e_f of an inhomogeneous foam layer. Based on this result, we used the LOCEAN e_f model for tuning of the foam properties.

3.2. Tuning the foam properties

Foam layer nominal thickness t_n (Section 2.2) varies linearly with changes in the upper limits v_{af} for frequencies from L to W bands. For each frequency, t_n changes by about 32% over the considered range of v_{af} values. We use as effective foam layer thickness the t_n values for each frequency averaged over the v_{af} range, i.e., $t_{eff} = \langle t_n \rangle$ (Table 1). As obtained, these t_{eff} values are suitable for both narrow range of v_{af} values (95% to 99% as typically used in e_f models) and for possible lower values in real conditions.

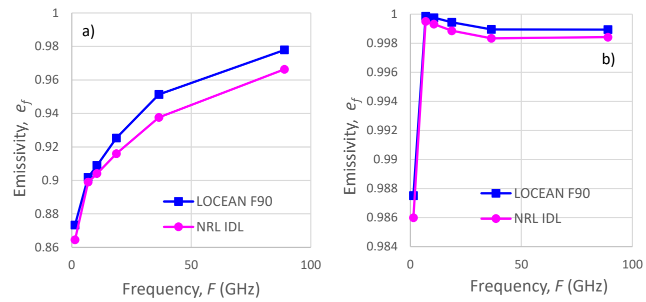

Figure 1: Frequency dependence of foam emissivity e_f from the original implementations of the LOCEAN (blue squares) and NRL (magenta circles) e_f models at polarization: a) H; b) V. Note the different scales on y axis.

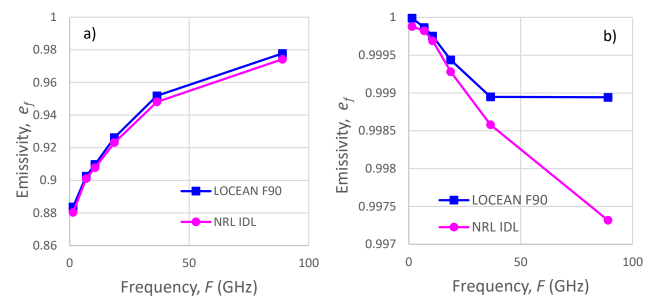

Figure 2: Frequency dependence of foam emissivity e_f from LOCEAN (blue squares) and NRL (magenta circles) e_f models with all elements the same but their formulation at polarization: a) H; b) V. Note the different scales on y axis.

Table 1: Foam properties (foam thickness and void fraction upper limit) for specific frequency and polarization.

F (GHz)	t_{eff} (cm)	v_{af} for V	v_{af} for H
1.4	2	0.95	0.95
6.9	0.6	0.95	0.96
10.6	0.4	0.95	0.964
18.7	0.2	0.95	0.968
36.5	0.1	0.98	0.97
89	0.1	0.97	0.98

With the chosen t_{eff} values for each frequency, we ran the LOCEAN e_f model with different increased v_{af} values until we obtained the smooth $e_f(F)$ curves shown in Figure 3. Table 1 gives the tuned v_{af} values.

3.3. Assessing the tuned foam emissivity

With the tuned LOCEAN e_f model, we ran the full RTM to obtain e for the three cases listed in Section 2.3. We obtained ΔT_B for each case using each 100th data point from the AMSR2 dataset (Section 2.3), i.e., 9873 data points. Figure 4 shows ΔT_B for X band (10.6 GHz), H polarization, binned by wind speed. The results for V polarization and all frequencies from C to W bands have similar trends.

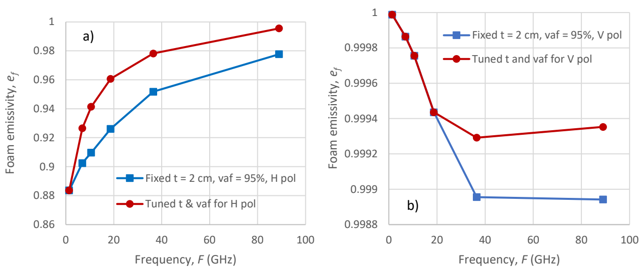

Figure 3: Frequency dependence of foam emissivity e_f from LOCEAN e_f model with fixed (blue) and with tuned (red) foam properties parameters at polarization: a) H; b) V.

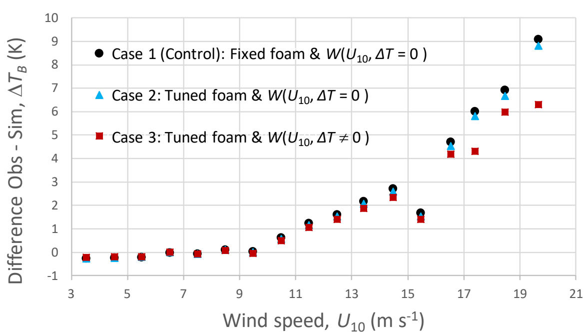

Figure 4: Difference between simulated and observed T_B at TOA for three case runs of the full RTM at X band, H-pol.

Figure 4 shows that the tuned foam properties (Case 2) yield noticeable yet slight decrease of ΔT_B compared to the control (Case 1). Thus, tuning the foam properties is not effective to sufficiently minimize ΔT_B. Optimization of the roughness and wave spectrum models for e in the full RTM should also be considered. Case 3 shows that the ΔT_B values decrease even more when more realistic W parametrization with additional variables (e.g., ΔT) is used. This justifies further work on developing improved W parametrizations.

4. CONCLUSIONS

We compare the implementations of two foam emissivity models (Figure 1) in the framework of an ISSI project aiming to develop reference quality RTM for the ocean surface emissivity e over wide range of frequencies (Section 1). The study considered three tasks (Section 2). The results support the following conclusions:

1) Semi-closed formulation of the incoherent approach for foam emissivity e_f is a good approximation of the most general formulation (Section 3.1 and Figure 2).
2) Foam emissivity is tuned by frequency and polarization via changes of the foam properties (Table 1 and Figure 3).
3) Use of tuned foam emissivity e_f model for e in a full TOA RTM improves the comparison between simulated and observed T_B slightly yet noticeably (Figure 4).
4) Whitecap fraction parametrization involving U_{10} and atmospheric stability more effectively minimizes ΔT_B than tuning the foam properties in e_f (Figure 4).

Future projects will investigate the wind speed dependence of the foam properties (void fraction and thickness) for more realistic tuning and will compare the considered physical e_f models to empirical e_f models such as [15].

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